The Association
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The Elements Of Industrial Radiography.

By S. V. RAINEY, A.I.Mar.E.,
and H. W. HOGBEN, M.B.E., B.Sc. (Eng.).

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THE ELEMENTS OF INDUSTRIAL RADIOGRAPHY.

. . . by . . .

S. V. RAINEY, A.I.Mar.E.,

. . . and . . .

H. W. HOGBEN, M.B.E., B.Sc. (Eng.)

I. INTRODUCTION.

The non-destructive examination of castings and welds in engineering by the use of X-rays is well-known, having been carried out for many years, and the employment, for the same purpose, of gamma-rays emitted from the naturally radioactive element, radium, has been practised to a certain extent. Radon, which is an active gas obtained by placing radium salts into solution and extracting the gas by the aid of vacuum pumps, supplemented radium as a source of gamma-ray emission but, for industrial applications, has certain disadvantages. As a result of the tremendous volume of research into nuclear energy during the last decade, and the introduction of the atomic pile, artificial radioactive isotopes have now largely replaced the more established sources of radium and radon.

Both X- and gamma-radiography are treated in the following pages. Apart from the succeeding chapter the first part of the work has been based on X-rays, features common to X- and gamma-rays being placed together. Sections dealing with the functions peculiar to gamma-rays follow, and the work concludes with some general considerations and notes on safety precautions.

This pamphlet is not intended to serve as a working guide for a radiographer. It has been written, primarily, from the draughtsman's viewpoint, and he is concerned, in the main, with two aspects of radiography. When can it be used? What does it reveal? Nevertheless it is essential that a modicum of the practical side be discussed together with the underlying principles of the method. In this way only may the possibilities, and the limitations also, of radiography be appreciated. The authors have been strengthened in their view that such treatment is necessary by the nature of the many questions they have received from members of the large drawing offices with which they are associated.

II. NATURE AND PROPERTIES OF X-RAYS AND GAMMA-RAYS.

X-Rays were discovered by Roentgen in 1895, and one year later Becquerel observed that uranium compounds emitted radiations which, like X-rays, could pass through opaque objects and blacken a photographic plate. This led to the isolation, by Mme. Curie and her husband in 1898, of radium. It was left to Rutherford and others to demonstrate that these radiations could be classified into alpha, beta and gamma-rays. No concern will be paid here to alpha and beta rays, which are known to be material particles.

X- and gamma-rays are high intensity electro-magnetic waves forming part of the electro-magnetic spectrum, together with cosmic rays, ultra-violet and white light, infra-red rays and radio waves. Light waves in the visible spectrum have wavelengths of the order of 10^{-5}cms., X-rays wavelengths of the order of 10^{-8} cms. and the hardest gamma-rays wavelengths of the order of 10^{-11} cms. It is well known that white light is completely absorbed by almost all matter except such items as glass and perspex. X- and gamma-rays, on the other hand, will penetrate all matter to an extent depending on the density of the substance through which they pass, and increasingly as the wavelength of the rays becomes shorter. Tungsten-alloys, for example, are more opaque than steel and both are more opaque than aluminium.

Photographic emulsions are affected by X- and gamma-rays and, therefore, a photographic record may be obtained after the rays have passed through a substance. This record will show the differential densities of the substance due to the selective absorption of the rays. When rays pass through an object, and traverse a cavity in that object no absorption will take place in the cavity. On emerging from the object, the intensity of the rays whose path lay through the cavity will be greater than that of the rays which have passed through homogeneous material. The effect obtained on the photographic film, or radiograph, is the production of a spot darker than the surrounding area. Similar conditions obtain for inclusions of lesser density than the parent body.

X-rays produce visible fluorescence in certain chemical compounds, and this property is turned to advantage in two ways. Firstly, intensifying screens of calcium tungstate can be used to reduce exposure times. When these screens are struck by X-rays, the light which is emitted aids the blackening of the film. The second application is called fluoroscopy where a fluorescent screen, taking the place of the film, emits light due to the action of the X-rays, and a visible but non-permanent record is obtained. As the use of fluoroscopy in industry is limited mainly to the examina-

tion of mass produced small items, it is not proposed to deal further with this branch of the subject.

The final property of X- and gamma-rays of any bearing on the scope of this present work is the unfortunate one of producing deleterious effects on and in the human body. The major troubles experienced in practice are those of burns, dermatitis and changes in the blood-forming organs leading to anaemia and leukaemia. Other serious evils, though of lesser occurrence, are the setting up of malignant tumours, loss of hair, cataract of the eye, impaired fertility and the shortening of the span of life.

III. THE PRODUCTION OF X-RAYS AND THE CONSTRUCTION OF X-RAY GENERATORS.

X-ray tubes now in general use are of the Coolidge high vacuum, hot cathode type, invented in 1913, which superseded the original gas filled tubes. As shown in Fig. 1, the tube consists of a highly evacuated glass bulb into which are sealed the cathode (negative electrode) and the anode (positive electrode). The cathode is usually made of molybdenum, or copper, and supports a tungsten filament, F, heated by a current supplied through a low voltage transformer. The anode consists of a copper arm supporting a block of copper in which is set a thin tungsten plate called the Target, T, which is maintained at a high potential relative to the cathode. When incandescence is reached in the filament, electrons are given off and are driven in a stream across the tube, by the high potential between F and T, towards the anode where they bombard the tungent target. After collision with the target, the kinetic energy of the electron is converted into another form reappearing as X-rays accompanied by considerable heat. Heat dissipation is assisted by the circulation of oil or water behind the target.

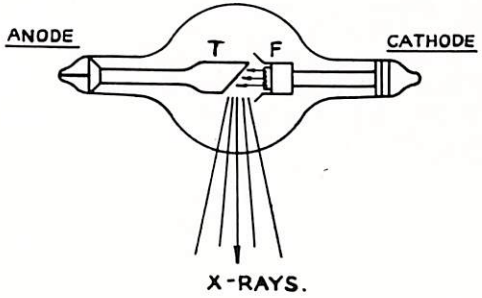
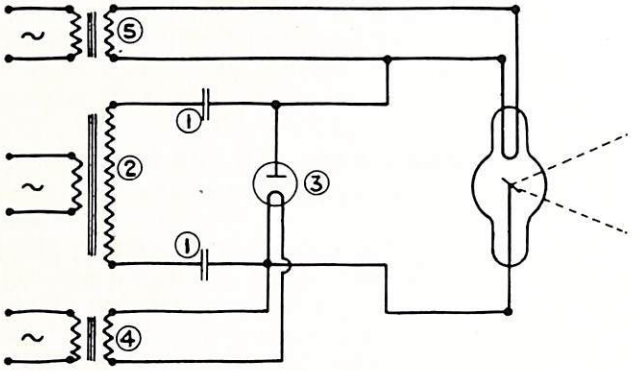


Fig. 1—Coolidge Bulb.

Electrical circuits for X-ray sets can be divided into low tension control and high tension generating circuits. The three basic controls required are for tube current, tube voltage and exposure time. On present day sets the exposure time is invariably controlled by an automatic timing device which stops the generation of X-rays after a pre-determined period.



1. CONDENSER.
2. H.T. TRANSFORMER.
3. RECTIFYING VALVE.
4. RECTIFIER TRANSFORMER.
5. X-RAY FILAMENT TRANSFORMER.

Fig. 2—Villard Circuit.

One of the most popular types of generating circuit in use at the present time is the Villard circuit, the basic diagram of which is shown in Fig. 2. Briefly, it employs a principle of voltage doubling, *i.e.*, the kilovoltage peak (KVp) applied to the X-ray tube is double the voltage supplied by the transformer. This is accomplished by inserting condensers (1) in the circuit, between the secondaries of the H.T. transformer (2) and the X-ray tube, and placing a rectifying valve (3) across the tube. Rectified pulsating potential is delivered to the X-ray tube. The greatest intensity and the highest quality of radiation from an X-ray tube are obtained, however, with constant potential output such as is given in a Greinacher circuit.

A typical X-ray machine is the Pantak model shown in Fig. 3. This unit, continuously rated at 150 KVp at 6 mA, is entirely self-contained apart from the connection to the mains voltage. The equipment has a high degree of mobility and portability, and as such finds extensive use in shipyards and in heavy engineering factories where it is not convenient to transport large specimens to the X-ray machine. There are two generator compartments,

one control compartment and one cooling compartment attached to the trolley together with the tube stand. For operation the components may be left on the trolley or they can be removed and carried separately by hand when space is a limiting factor; for example in ships under construction. The design of the tube stand enables a wide range of positions to be obtained. Cooling of the tube is effected by a water pump which is kept supplied by a header tank. The control panel for this set is shown in Fig. 4. It is important to note that X-rays cannot be generated unless the filament is switched on and the KV control set at zero. Compensation can be made for fluctuations in the mains supply, and the cooling pump starts up when the mains switch is closed. The reading on the primary voltmeter is an indication of the X-ray tube potential and in conjunction with the tube current enables the operating KV to be determined from a calibration chart. Protective devices guard the set against (1) restriction of cooling water; (2) overheating; (3) excessive tube current.

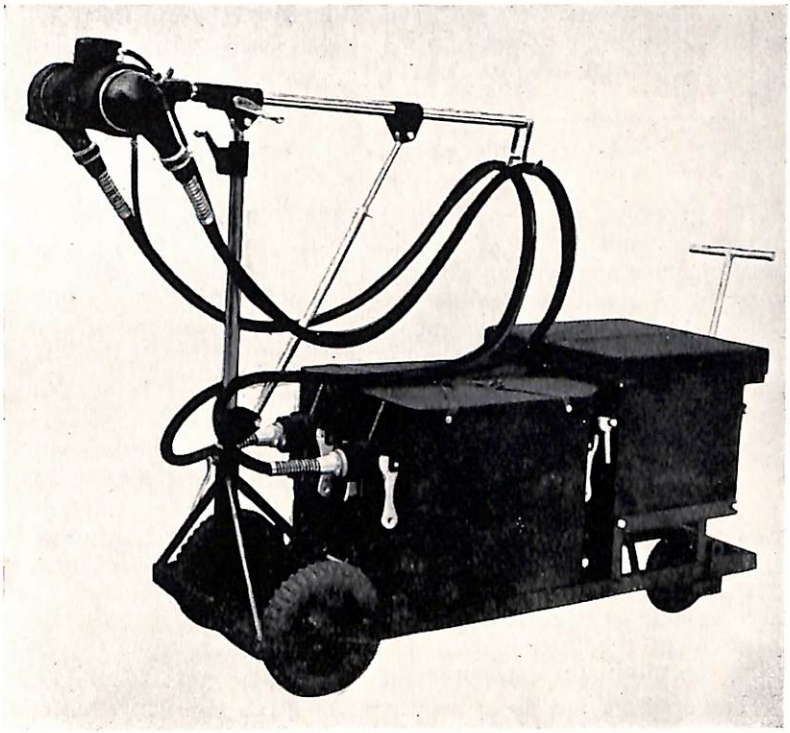
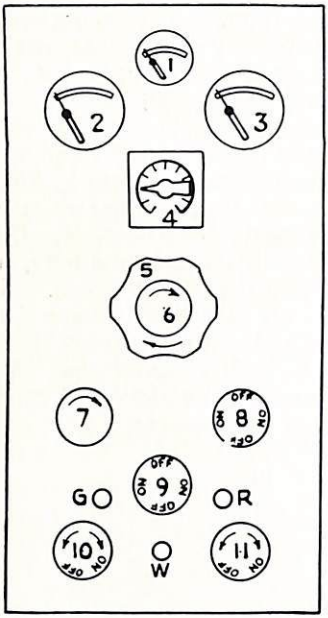


Fig. 3—Pantak 150 KVp X-Ray Set.



KEY.

1. MAINS VOLTMETER.
2. MILLIAMMETER.
3. PRIMARY VOLTMETER.
4. TIMER.
5. MAINS COMPENSATION.
6. KV CONTROL.
7. mA CONTROL.
8. TIMER SWITCH.
9. MAIN SWITCH
10. FILAMENT SWITCH.
11. H.T. SWITCH. (X-RAYS)

G. GREEN LIGHT - FILAMENT 'ON'
R. RED LIGHT - X-RAYS 'ON'
W. WHITE LIGHT - COOLANT 'ON'.

Fig. 4—Control Panel.

In general, X-ray equipment must combine the maximum mechanical and electrical flexibility with tube stand rigidity to prevent movement during exposures. The focal spot of the target must be as small as possible to avoid penumbral effects on the radiograph, and the whole apparatus must be shockproof. The majority of machines in use are of 300 KVp or less, with isolated cases of machines up to 1000 KVp, *i.e.*, 1 million volts.

IV. THEORETICAL CONSIDERATIONS (X-RAYS).

The primary object of a radiograph, in the majority of cases, is to detect the smallest defect present in the greatest thickness of given material. From an economic point of view, especially if a large volume of work is handled, it must be added that the above requirement should be obtained in the shortest possible time, *i.e.*, using the minimum exposure.

The operator has no control over the given object, its material, thickness or shape. He has some control, however, over the operation of the X-ray set, the type of film and screens used, and

the position of the source of X-rays relative to the film. The problem facing the radiographer is the co-ordination of all the variables in order to produce the best possible radiograph. It is proposed to take in turn all those factors which must be borne in mind, and to define certain common radiographic terms in order to familiarize the reader with the technical jargon of the subject.

(1) **Kilo-voltage of the X-ray Tube.**—The greater the voltage applied to the tube, the shorter will be the wavelength and the greater the penetrating power of the rays produced. Obviously, the thicker the specimen under examination the higher is the voltage required. A limit, however, is set to desirable voltage increase by the decrease in image contrast at high voltages which may impair the efficiency of the inspection.

(2) **Tube Current** (milli-Amperes).—The intensity of radiation from an X-ray tube is directly proportional to the current passing through it. It is, therefore, good practice to use the highest possible tube current. For example, similar results will be obtained with an exposure of 1 minute at 10 mA, as from an exposure of 2 minutes at 5 mA, providing other conditions remain unchanged. This relationship does not, however, always hold good when fluorescent intensifying screens are used.

(3) **Exposure Charts.**—Figures 5 and 6 give typical exposure charts for the examination of steel and aluminium. They show the inter-relation of KV and mA for varying thicknesses, and it will be noted that mA and exposure time are combined as a product. It is important to realise that the charts are for set conditions of (*a*) source-film distance ; (*b*) type of film ; (*c*) intensifying screens, if any, and (*d*) radiographic density. Adjustments to exposure time will be required if any alterations are made to the set conditions. It cannot be too strongly emphasised that any exposure chart will apply only to that X-ray tube for which it was established. Individual tubes have their own characteristics, with corresponding effects on an exposure chart, and indeed it is often necessary to re-establish an exposure chart during the life of a single tube.

(4) **Source-Film Distance (S.F.D.).**—Otherwise called target-film distance or focus-film distance. This is the distance between the source of the X-rays and the film, which is placed on the side of the specimen remote from the source. With reference to Fig. 7 where S is the source of X-rays, it will be seen that the intensity of the beam at A, distant D from S, is four times the intensity at B, distant 2D from S, due to the progressively larger area being covered. This is known as the *inverse square law* which states that the intensity of radiation at any point varies inversely as the

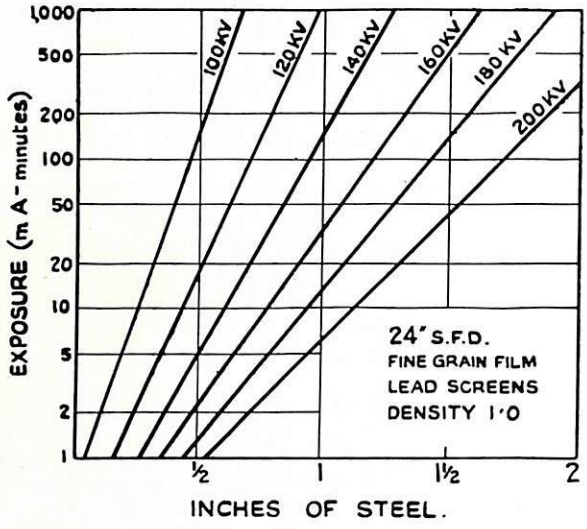


Fig. 5—Exposure Chart. (Steel).

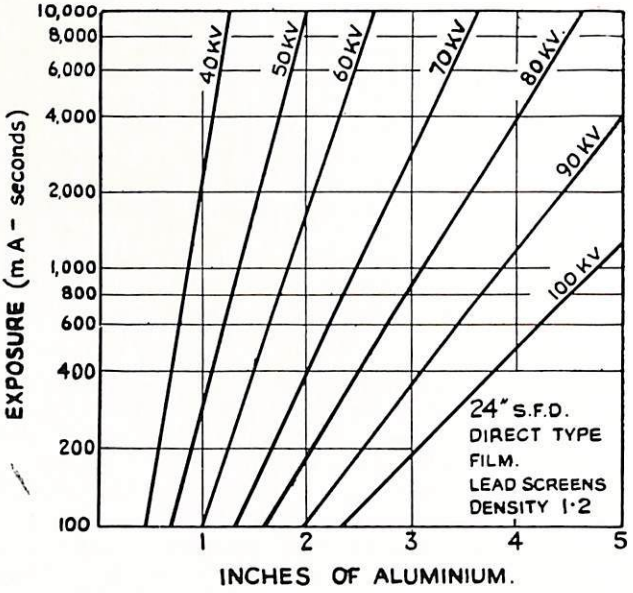


Fig. 6—Exposure Chart. (Aluminium).

square of the distance from the source to that point. Hence, other conditions being equal, an exposure of 1 minute at 18″ S.F.D. will give the same result as an exposure of 4 minutes at 36″ S.F.D. From an economic angle it may be thought that it would pay to use a very short S.F.D. thus reducing exposure time to a minimum. This leads appropriately to the following section dealing with questions of geometry.

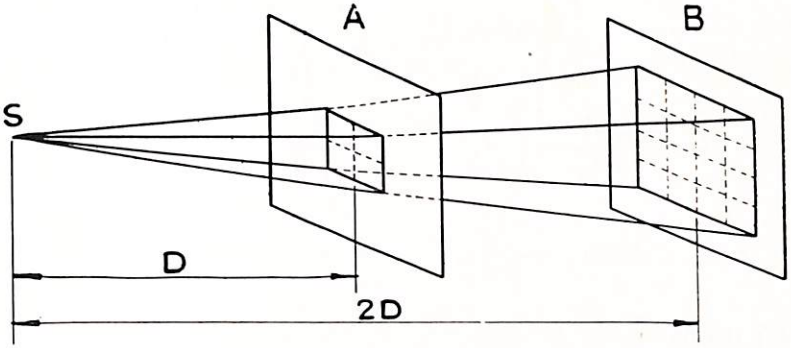


Fig. 7—Inverse Square Law.

(5) **Geometry and Definition.**—It is important to remember that a radiograph is a shadow picture of the object under examination. The darkest portion of the radiograph represents that part of the object most transparent to X-rays, and the lighter portions those parts which are less transparent. The true shadow will be surrounded by a penumbra, P, (see Fig. 8) across which the radiographic density gradually changes. This penumbra blurs the outline of the shadow image and if the image is a faint one it may not stand out from its background. P must be as small as possible in order to produce a sharp and true shadow of an object. A study of the diagrams in Fig. 8 will suffice to show that, to achieve this, the source should be as small as possible and as far away as possible from the object. The film should be as near as possible to the object, and normal to the perpendicular from the source to the object. Ideally, of course, the source should be a point, but this can never be attained in practice. The definition of a radiograph refers to the sharpness with which the outlines of faults or variations in object density are revealed.

The size of the source, or focal spot, is outside the control of the radiographer. Where S.F.D. is concerned he must compromise between a short S.F.D. for economic exposure times or a long S.F.D. for good definition.

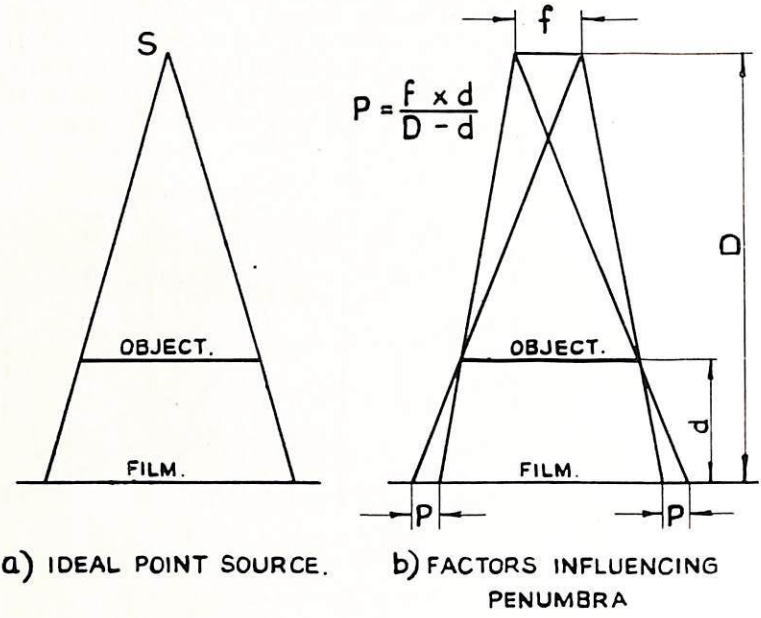


Fig. 8—Geometry.

(6) **Radiographic Density.**—The density of a radiograph is dependent upon the quantity of radiation reaching the film emulsion. The quantity of radiation depends, in its turn, on the operating KV and mA of the X-ray set, exposure time, the use of intensifying screens and the S.F.D.

The density is measured by the amount of the light transmitted when the radiograph is held up to an illuminator for viewing. If I_1 is the intensity of the light falling on the radiograph and I_2 is the intensity of the light transmitted through the radiograph then density is defined as $\log_{10} \frac{I_1}{I_2}$. Thus a film density of 1·0 indicates the blackening of the film to be such that 10% of the incident light passes through.

In general practice a density of between 1·5 and 2·5 is aimed at although in special cases densities as high as 4·0 have been employed. The use of high densities, however, requires high intensity illumination for the satisfactory interpretation of radiographs. From this point onward the term density will refer to radiographic, and not material, density unless otherwise stated.

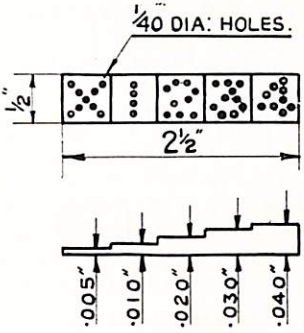


Fig. 9—Penetrameter. B.W.R.A. Type.

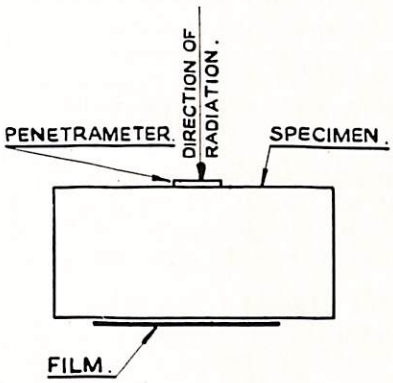


Fig. 10—Application of Penetrameter.

(7) **Radiographic Sensitivity** is the ability to detect faults or discontinuities in the object examined. Sensitivity is usually expressed as a percentage of the total thickness :—

$$\text{Sensitivity, } \% = \frac{\text{Smallest thickness visible in radiograph}}{\text{Total thickness of object}} \times 100$$

Since the thickness of an internal defect cannot be measured, the thickness of the object is increased artificially by a device known as a penetrameter, of the same material as the object. A widely used type of penetrameter (British Welding Research Association step-wedge) is illustrated in Fig. 9, and its application in Fig. 10. The penetrameter is graduated in steps of ·005", 010", ·020", ·030" and ·040", with tiny holes drilled in the shape of

figures for purposes of identification. The sensitivity is then measured by the thickness of the thinnest step visible on the radiograph expressed as a percentage of the object thickness. In Fig. 10, if the first step visible is ·020″ thick, and the object is $1\frac{1}{8}$″ thick, then the sensitivity is $\frac{\cdot 020}{1 \cdot 125} \times 100 = 1 \cdot 78\%$.

It will be obvious that the sensitivity thus recorded is not the true value. To obtain a true value it would be necessary to have an infinite number of steps on the penetrameter. It can be said only that the sensitivity given by this method is below a certain value. In the example given above the sensitivity is below 2%.

The lower the percentage recorded the higher the sensitivity, which is a test of the quality of the radiographic technique. A sensitivity of 2% is usually regarded as adequate, although sensitivities of $\frac{1}{2}$—1% are often obtainable with thicknesses below $1\frac{1}{2}$″. Great care must be exercised when determining the thinnest step visible on a radiograph. Pre-knowledge of the shape of the penetrameter may lead one to imagine the presence of a thinner step than is actually visible. This is overcome by covering each succeeding step with a piece of paper until no further steps are visible.

The penetrameter is usually placed on the same side of the object as the source. This is not always possible and tests have shown that little loss of measurable sensitivity occurs in cases where the penetrameter is on the same side as the film.

(8) **Radiographic Contrast** is the difference in blackening on a radiograph resulting from variations in object thickness or material density. The greater the contrast the easier it will be to detect flaws on a radiograph. It will be appreciated that definition, sensitivity and contrast are all interdependent. Contrast decreases with increase in the tube KV and also with X-ray scatter. It increases with density up to a figure of about 1·3, above which only slight changes occur.

(9) **X-Ray Films.**—In general there are three main types of films used in this country. *Screen* type film is a general purpose film for use with fluorescent intensifying screens. It possesses high speed and high contrast. When used with lead screens the contrast obtained will be lower. *Direct* type film is intended for use with direct radiation or with lead screens. It possesses high contrast and good speed, while the image obtained is sharper than with screen type film. Finally there is the *fine grain* film. The finer the grain of the film the better the definition, and this type of film is particularly valuable when fine detail is wanted or minute flaws are suspected. It is intended for use with direct radiation

or with lead screens. Fluorescent screens are not used with this type of film as the advantage of the fine grain would be destroyed. It possesses high contrast, but has a speed of only 1/5 - 1/3 that of the direct type film. There are other films in use but these are confined generally to special cases.

(10) **Intensifying Screens.**—These are of two kinds, *fluorescent* (salt) screens or *lead* screens. As noted in Chapter II, certain chemicals have the property (fluorescence) of absorbing X-rays and emitting visible light. Calcium tungstate, or zinc sulphide, is spread over cardboard sheets which are placed in contact with both sides of the film. The visible blue-violet light emitted reacts on the film emulsion, intensifying the radiographic effect and reducing exposure time. Fluorescent screens may be sub-divided into two types; *ultra-speed* and *high definition*. Ultra-speed screens have an intensifying factor of 30-150 (*i.e.*, the exposure time is reduced 30-150 times) depending on tube voltage, material density and thickness.

$$\text{Intensifying factor} = \frac{\text{Speed with screens}}{\text{Speed without screens}}$$

High definition fluorescent screens have a lower intensifying factor than ultra-speed screens due to the finer grain of the crystals, but, as the name implies, better definition is produced. It must be remembered that gain in speed is offset by reduction in quality of the radiograph. For this reason the use of fluorescent screens is not regarded as being of first-class technique. The action of lead screens depends on the emission of secondary electrons through absorption of photons by the lead. The electrons emitted produce an effect of intensification similar to that from the visible radiation of fluorescent screens. The intensifying action of lead screens, however, is slight and their main purpose is to reduce the effects of scattered radiation. Lead screens are used also on both sides of the film, ·002″ front and ·005″ back screens being typical values. They have an intensifying factor from 2-5 for X-rays between 100 and 200 KV. It is most important that all types of screens be kept free from dust, grit or scratches as images of these may appear on the radiograph.

V. PRACTICAL ASPECTS. (X-RAYS).

Before making a radiographic examination it will be found helpful to study a drawing of the object, if one is available. All parts examined should be as clean as possible. Castings should be fettled and free from sand; welds should be ground flush with the parent metal, if practicable, and free from surface slag, spatter and chipping marks. All surface marks should be noted so that,

should they appear on the radiograph, they will not be mistaken for internal defects. It is worth remembering that casting thicknesses are often greater than called for on a drawing. If the examination is being carried out for a recognised inspecting authority their rules relating to radiographic technique must be respected.

In choosing the maximum length to be examined on one exposure, it is a general rule that the thickness to be penetrated at the ends should not exceed the normal metal thickness by more than 10%—see Fig. 11.

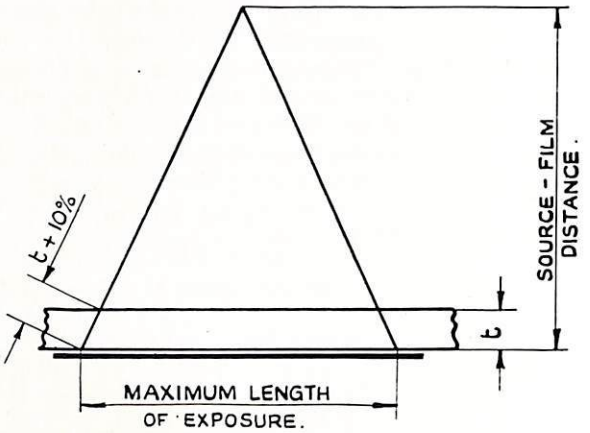


Fig. 11—Limit on Thickness.

It must be possible at all times to correlate the radiograph with the specimen. The area to be examined must be marked out and identification numbers stamped or painted on. Lead figures are then placed to coincide with the stamped numbers, and where more than one exposure is required to cover the area sufficient overlap must be provided to ensure that every portion is examined. Identification should appear also on the overlap. The general scheme is shown in Fig. 12. Such identification markings will appear on the radiograph, and provide subsequent datum points for locating flaws in the material or proof, against possible future enquiry, that a specimen has indeed been examined.

Wherever possible changes of thickness should be avoided on one film. Sometimes, however, a fast and a slow film are exposed simultaneously in the same holder (cassette). The faster film would be used to examine the thick portion, and the slower film the thin portion. On the faster film the thin section would appear too dark for adequate interpretation, and penetration of the thick section would be insufficient on the slower film.

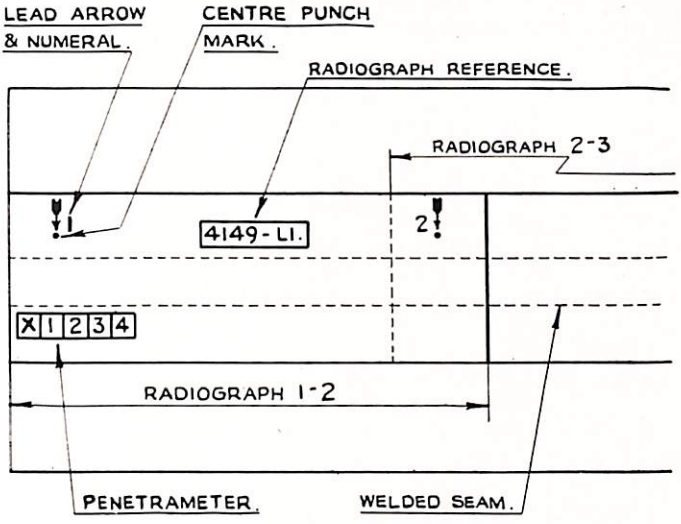


Fig. 12—Layout for Identification.

The radiographer will not always be able to achieve a perfect set-up. Fig. 13 indicates the double wall technique required for a welded tube in cases where it is not possible to place the film in the ideal position inside the tube. The weld may appear on the radiograph in the form of an ellipse. The portion of the weld nearest to the film will admit of the best interpretation, and it is preferable to make at least four exposures around the circumference to cover the entire weld in an adequate manner.

The film should always be placed as close as possible to the particular section which is under examination. Fig. 14 illustrates the difficulty of producing satisfactory radiographs of fillet welds : (*a*) the film is away from the weld under investigation, and in both (*a*) and (*b*) the variation in the thickness will be noticed. The detection of internal cracks will depend on the relation of the crack to the direction of the X-ray beam. With reference to Fig. 15 the crack shown in sketch (*a*) will appear on the radiograph, but there would be no evidence of the crack in sketch (*b*). This explains the inability of X-rays to detect laminations in rolled plates. Fortunately, in most objects examined a crack rarely lies wholly in one plane.

In cases where there is a known flaw in the object, and it is desired to locate its depth below the surface the simple method shown in Fig. 16 may be adopted. In this method two exposures are made on the same film with the X-ray tube in two different

positions, S_1 and S_2. The depth of the flaw is calculated from the shift of the flaw image on the radiograph from position P_1 to P_2 whence :—

$$d = \frac{L \times D}{L + F}$$

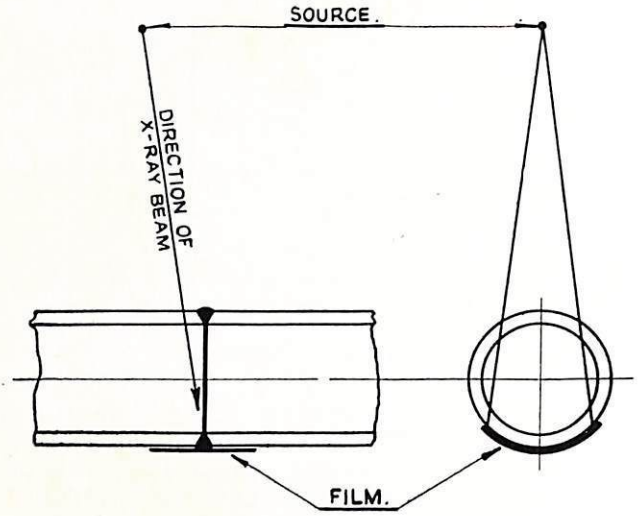


Fig. 13—Double Wall Technique.

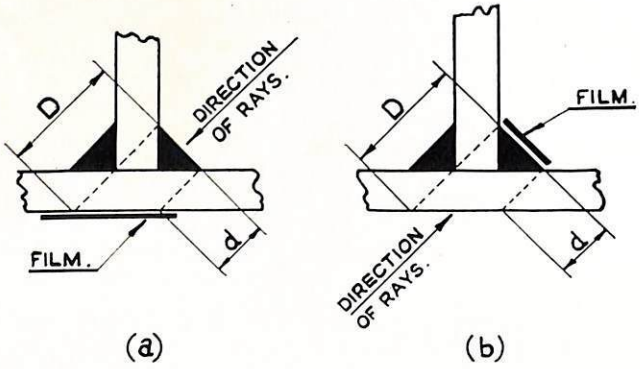


Fig. 14—Radiography of Fillet Welds.

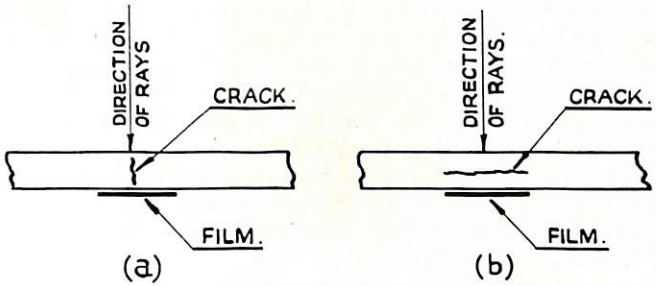


Fig. 15—Detection of Cracks.

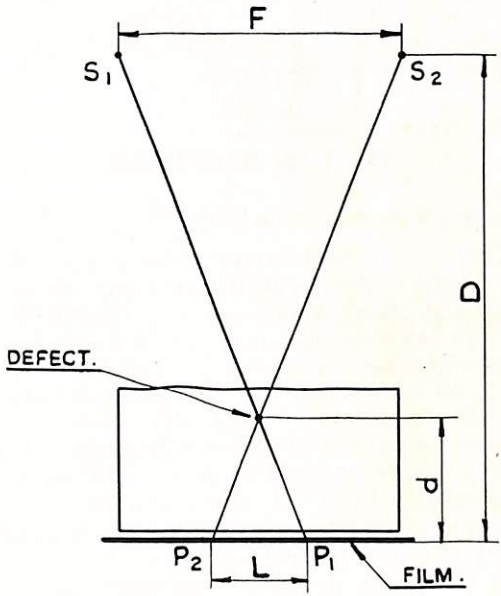


Fig. 16—Flaw Location by Double Exposure Technique.

One of the greatest troubles experienced in practical work is the effect of scattered radiation, not only from the specimen itself but from surrounding objects including walls and the floor. Unless precautions are taken to counter this scatter the radiograph will be covered with a general haze, resulting in a lowering of contrast. Methods employed to eliminate scatter include covering the back of the cassette with lead sheet, restriction of the X-ray beam by attaching a lead cone to the tube and ensuring that metallic objects in the vicinity are either removed or covered with lead sheet. Scattered radiation from the specimen itself can be dealt with by inserting a filter in the X-ray beam, to absorb the soft rays most likely to give rise to scatter, and the use of the Potter-Bucky diaphragm.

It is essential, but sometimes difficult of achievement, to ensure that the film, inside whatever type of cassette may be used, is firmly secured so that it does not move during the exposure. In the case of ferrous metals small magnets are widely used for attaching the cassette to the specimen.

Having settled on the best way to attack his problem, the radiographer can then select tube voltage and current, S.F.D., film and screens, and adjust his exposure time to give a radiograph of suitable density and sensitivity.

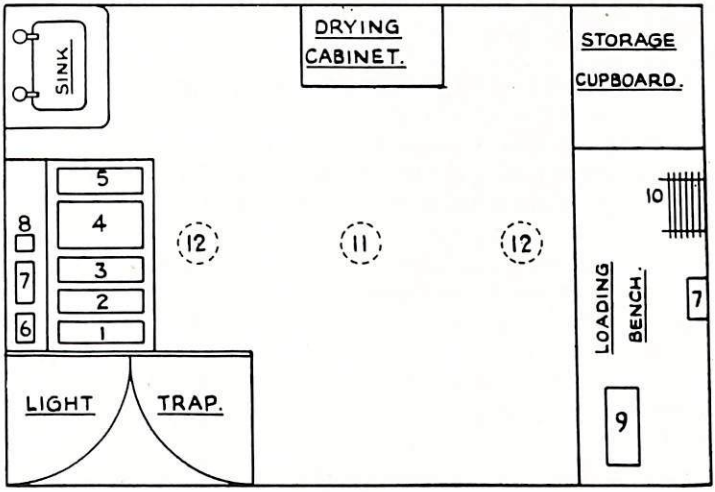
VI. THE DARKROOM.

A darkroom serves four main purposes :—

(1) Loading of films and screens into cassettes before exposure and unloading prior to development, under safe lighting conditions ; (2) Processing and drying of radiographs ; (3) Provision of correct illumination for viewing and interpreting finished radiographs ; (4) Storage of films and accessories. A typical layout for a radiography darkroom is shown in Fig. 17 and the following points are important. The room must be lightproof with entrance through a light-trap, and if situated adjacent to the X-ray exposure room it must be thoroughly screened to prevent the admission of stray radiation harmful to films. It is essential to have thermostatic temperature control for processing, and the radiographs should be allowed to dry in a dust-free cabinet rather than in the open room. The benches for loading and unloading films should be kept well clear of the processing unit and sink.

The function of processing is to turn the exposed film into a finished radiograph. Under correct safe-lights the exposed film is removed from its cassette and transferred to a hanger. It is then placed in a deep tank containing the developer which acts on

the exposed crystals of silver halide, changing them to black silver grains and making the latent image visible. Factors influencing development are the developer itself and its temperature, the time of immersion, the film and the extent to which the developer has been exhausted by previous use. Standard development time is 5 minutes at 68°F. and this must be corrected for any change in temperature. The film should be agitated at intervals during developing to ensure even development and avoid flow marks. After development the film is rinsed in water for approximately 30 seconds to remove surplus developer remaining on the film. Transfer is then made to the fixing tank. Here the development is stopped and all undeveloped silver halide crystals, which would tend to confuse the image, are removed. While in the fixing tank the white "haze" on the film surface gradually disappears. The film should remain in the fix for double the time taken for the haze to clear. Agitation is again necessary to ensure uniform action of the chemicals. White lights may be switched on after the film has cleared. On completion of fixing the film is immersed in a bath of running water for half-an-hour to dispel the fixing chemicals. Finally it is dipped into a rinse bath containing a wetting agent



1. DEVELOPER.
2. RINSE.
3. FIX.
4. WASH.
5. FINAL RINSE.
6. CLOCK.
7. WALL SAFE LIGHTS.
8. THERMOSTAT CONTROL.
9. ILLUMINATOR.
10. HANGER RACKS.
11. CEILING SAFELIGHT
12. WHITE LIGHT.

Fig. 17—Darkroom Layout.

to aid the elimination of water droplets while drying, removed from the hanger, suspended on clips, and allowed to dry in the cabinet usually assisted by the circulation of warm air.

After drying, the radiograph is ready for viewing on the illuminator. Radiographs are always examined in the negative state owing to the loss of detail in any prints which are taken off the negative. The illuminator should be capable of lighting up the highest density on the radiograph, and it is preferable when viewing radiographs to have subdued or almost total absence of extraneous light. The practice of viewing radiographs in a wet state is to be discouraged owing to the possibility of misinterpretation.

The standards attained in darkroom work will be reflected in the presence or absence of fortuitous images (artifacts) on the finished radiograph. Such images cause confusion during interpretation, and it is possible for a sound specimen to be condemned due to a blemish on a radiograph being incorrectly diagnosed as a material flaw. A few of the many possible causes of trouble are pressure marks occasioned by careless handling of the film at any time ; scratches or marks on intensifying screens ; faulty safe-lighting ; greasy fingers ; splashes. Finally, the importance of standardisation of development technique cannot be over-emphasised.

VII. INTERPRETATION.

There are three phases in radiographic interpretation :—

(1) Judging the quality of the radiograph itself, which involves a complete knowledge of the technique employed in producing the radiograph.

(2) Detecting and classifying the flaws shown. This not only assumes that the radiographer can recognise any type of flaw, but also that he is conversant with the manufacturing processes used in engineering.

(3) Deciding whether the specimen which has been radiographed is acceptable, and this usually involves a knowledge of the conditions to which the specimen will be subjected in service.

Phase 3 will be governed by the reason behind the radiographic inspection. This will have been due to compulsion, psychology or development. *Compulsion* where the customer or recognised inspecting authority calls for radiography. *Psychology* where an attempt is being made to induce improved standards of workmanship among welders or in the foundry. *Development* for investigation and improvement of welding and casting methods.

Acceptance standards, where such exist, are empirical in nature due to their being based entirely on experience. The difficulty

of establishing standards is due to insufficient evidence concerning the effect of sundry types of flaws on the performance in service of parts examined. It must be admitted that in some cases the final test is "when in doubt, cut it out." This is not as bad as it may seem; even if this is the final criterion, subconsciously the service conditions will have been estimated.

Where inspection is to customer's requirements the standard of acceptance is usually by agreement between customer and manufacturer, the service function of the specimen again being the governing factor. For ship welding the standard is controlled, perforce, by the fact that only a minute percentage of the total welds can be examined. This is due to the cost involved and the time that would be taken to carry out a complete radiographic inspection. Ship welds selected for radiography are those at critical stress points and representative welds of any form to cover each welder employed. Although serious defects are cut out when discovered, it must be appreciated that more serious defects may lie in unexplored welds. The primary aim, therefore, in ship welding is to establish and maintain a high standard of welding by psychological methods.

In the notes on interpretation which follow it is assumed that all surface marks have been noted, and the radiograph processed perfectly without fortuitous images. The notes are confined to the interpretation of flaws in radiographs of welding and casting, these forming the bulk of work undertaken in the engineering industry.

The illustrations accompanying this chapter give a general idea of what radiographs look like, bearing in mind the inevitable loss of detail during reproduction. The radiographs as shown are in the negative state, *i.e.*, as they would be viewed in normal practice. The flaws described will have the same general radiographic characteristics whether produced by X- or gamma-rays.

(A) **Welding Defects.**

Lloyd's Class I welding covers high duty pressure vessels containing toxic or lethal substances, or for use at high temperatures or pressure. Such work demands 100% radiographic inspection on all welds to be carried out by an approved radiographer and the welds must be completely free from defects of any kind. Where standards of acceptance are given below these refer to high class welding which is, however, below Class I standard. The terms used are the approved standard terms designed to eliminate the confusion which has existed in the past.

(1) **Undercut** (Figs. 18 and 19) is a groove or channel in the parent metal along the toe of a weld. It may occur either on the

Fig. 18—Undercut and Incomplete Root Penetration.

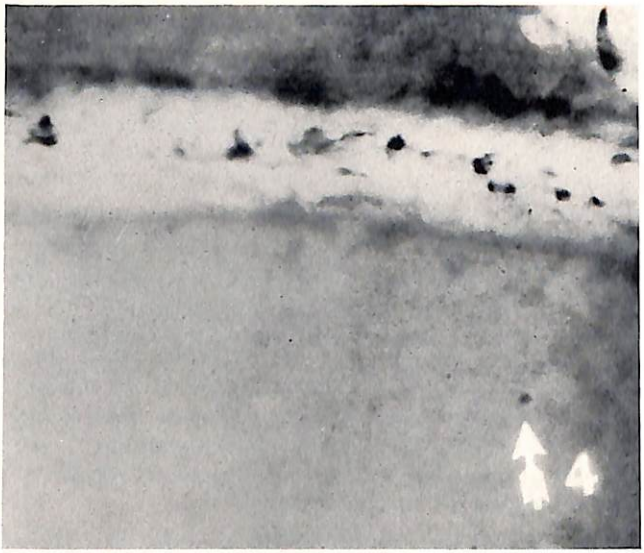


Fig. 19—Slag Inclusions (also showing Undercutting).

surface or in the fusion faces of multi-run welds, and may cause slag inclusions in the next run of weld. Undercutting appears on a radiograph as dark irregular bands along the edges of the weld. The cause is normally the use of excessive welding current or incorrect technique. For static loads small intermittent undercutting may be accepted. For fluctuating loads the fatigue resistance of the weld will be reduced, and the undercutting should be corrected.

(2) **Inclusion** (Fig. 19) is slag or other foreign matter trapped in the weld, slag being any non-metallic matter usually formed by the electrode covering. An inclusion is usually more irregular in shape than a blowhole (see 3*a* below) and of lower contrast on the radiograph. Inclusions are of three kinds :—

(a) *Large isolated inclusion*—appearing in a radiograph as a dark image with an irregular boundary, sometimes with density variations within the image.

(b) *Cluster of small inclusions*—appearing as a group of dark diffused spots.

(c) *Line inclusion*—appears as a dark wavy shadow along the weld.

A major cause of slag in the weld is poor cleaning between runs. Inclusions of type (*a*) and (*c*) will tend to reduce the strength of a weld, and it must be remembered that inclusions often lead to cracks. Small isolated inclusions of rounded outline may generally be accepted. For high quality work the following guide for acceptance may be used ; where t is the plate thickness the longest inclusion should not exceed $t/3$ and the added length of all inclusions should not exceed t in a length of 12 t. The distance between any adjacent inclusions should not be less than 6 times the length of the largest inclusion.

(3) (*a*) **Blowhole** is a large cavity formed by gas which fails to escape as the weld cools and is usually applied to cavities greater than $\frac{1}{16}''$ in diameter.

(*b*) **Gas Pore** is a small cavity due to entrapped gas and is applied to cavities less than $\frac{1}{16}''$ in diameter.

(*c*) **Porosity** is a group of gas pores and may occur as clusters, in chains or scattered.

The above three defects appear radiographically as dark shadows of rounded outline. Fig. 20 shows chain porosity in an aluminium weld, composed mainly of small gas pores with occasional blowholes. Fig. 21 is a section of a similar weld showing blowholes revealed by radiography. Trapped gas in the weld is formed by chemical reaction during welding, and is often associated with damp electrodes or high sulphur content of plate and electrode. Porosity

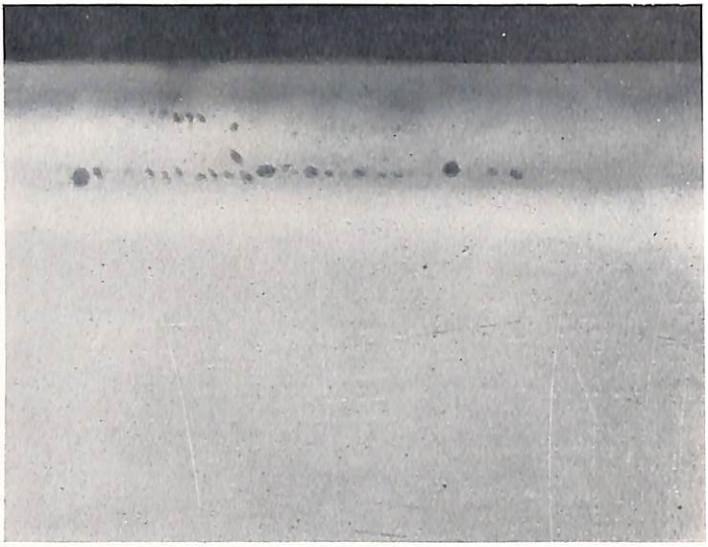


Fig. 20—Porosity (Radiograph).

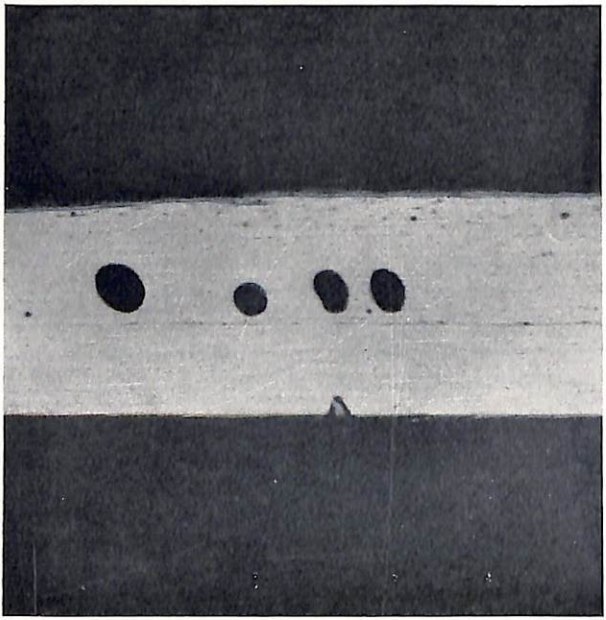


Fig. 21—Porosity (Sectioned and Enlarged).

reduces the effective area of a weld. For high quality welding the acceptable maximum diameter of individual images should not exceed $\frac{1}{16}$" dia. for plates up to $\frac{1}{2}$" thick, $\frac{3}{32}$" dia. for plates $\frac{1}{2}$" - 1" thick, $\frac{1}{8}$" dia. above 1" thick. For chain porosity adjacent gas pores must be at least $\frac{3}{8}$" apart.

(4) **Pipe** (or worm hole) is an elongated or tubular cavity due to entrapped gas. It is a porosity defect and appears as a dark shadow but, unlike 3 above, usually has an elongated shape at an angle to the weld.

(5) **Capillary Pipe** (base metal crack), see Fig. 22. This is a fine pipe extending along the junction of a weld and the parent metal. It appears in the radiograph as a straight dark diffused line. The cause can be traced to defects such as a lamination in the parent metal, which has opened out during the welding operation. It occurs in such examples as the welding of a dished end on to a solid drawn tube. In the majority of cases this leads to the scrapping of the parent metal even though the weld is of good quality.

Fig. 22—Capillary Pipes in Parent Metal.

(6) **Lack of Fusion** is the failure to unite between parent metal and weld metal, or between weld metal and weld metal, or between parent metal and parent metal as in the cases below :—

(a) *Lack of Root Fusion* is a discontinuity between weld metal and parent metal or between adjacent parent metal faces at the root. Radiographically it appears as a dark straight line sharply defined, but of low intensity.

(b) *Lack of Side Fusion* is a discontinuity between weld metal and parent metal at the side of the weld, and in appearance on a radiograph is similar to (*a*) above.

(c) *Lack of Inter-run Fusion* is a discontinuity between adjacent runs of weld metal. It appears in a radiograph as a faint line with the edges well-defined.

The form of the image depends on the angle of the X-ray beam and is revealed best when the beam is adjusted so that its direction is parallel to the weld interface and not in the normal position which is perpendicular to the top face. Fig. 23 is an enlarged

Fig. 23—Lack of Fusion (Sectioned and Enlarged).

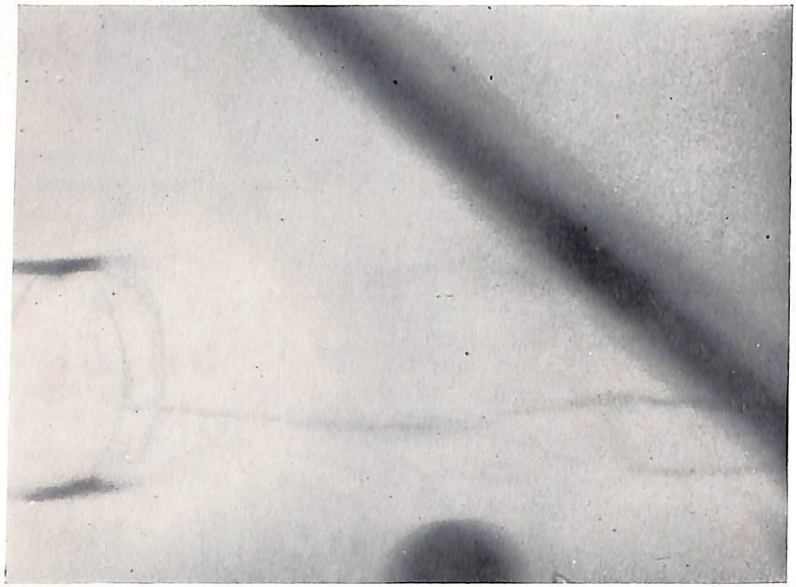


Fig. 24—Crack (the dark sloping band is a gap between two Backing Plates).

section through an aluminium weld, with backing strip, showing lack of side fusion. The horizontal gap is between the plate (top) and the backing strip (bottom) ; the vertical gap is the lack of side fusion between (i) plate and weld metal ; (ii) backing strip and weld metal. This defect was discovered by radiography but it has not been possible to reproduce the radiograph showing the lack of fusion.

This type of fault is associated with the presence of foreign bodies which prevent the metal from attaining fusion temperature, and may be caused also by the use of incorrect welding current. It is, therefore, quite common to observe slag inclusions present with lack of fusion. Even for static loads the strength of welding having lack of fusion may be too low, and for fluctuating loads cannot be accepted. Where t is the plate thickness the added length of all lack of fusion lines should not exceed $t/3$ in a length of $6t$ for good quality welding. For thin plates any lack of fusion should not be accepted.

(7) **Incomplete Root Penetration** (Fig. 18) is a gap left by failure of the weld metal to fill the root. It appears as a dark line, fairly continuous, with one or both edges straight along the centre of the weld. This defect may occur also when the weld metal fails to fill a crevice left by a previous run and in this case is known as *incomplete inter-run penetration*. The defect is due to incorrect size of electrode, incorrect welding current or unsuitable preparation of the joint. Incomplete penetration lowers the resistance of the weld to fatigue under loading of a fluctuating nature. Good quality welding will be subject to acceptance for incomplete penetration to standards as laid down for lack of fusion in (6) above.

(8) **Crack** is a discontinuity caused either by tearing of the metal while in a plastic condition (hot tear), or by fracture when cold (cold crack). Radiographically it appears as a dark, well-defined line. If the plane of the crack deviates from the plane of the X-rays it will appear as a broad ill-defined beam. Fig. 24 shows a crack in $2\frac{1}{2}''$ thick steel plate revealed by gamma-ray emission from a cobalt-60 radio-isotope. Cracks are generally caused by high local stresses due to weld metal shrinkage, or too high a degree of restraint of the parts being welded. It is obvious that for all classes of work cracks should not be permitted.

(B) Casting Defects.

Radiographic examination of castings is less well covered by codes and acceptance standards than the radiography of welding. Broadly speaking the examination of castings falls under three headings :—(*a*) for castings having to withstand high tensile stress or elevated temperatures ; (*b*) for castings where failure in service

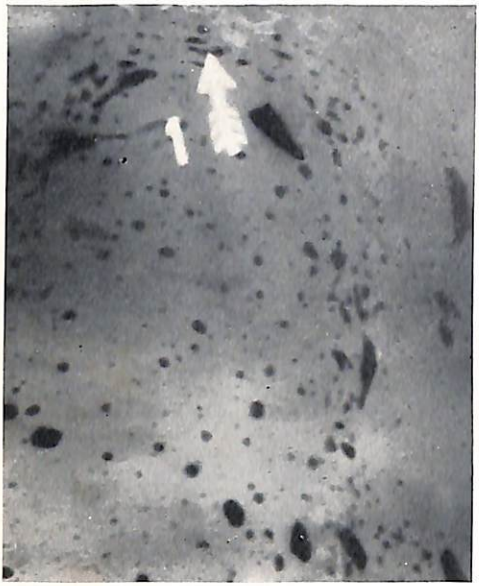


Fig. 25—Sand Inclusions and Porosity.

Fig. 26—Hot Tear.

would cause loss far in excess of the value of the casting, and (*c*) for castings requiring extensive machining.

Acceptance centres around the nature of the service performed by the casting, the size and position of defects and the type of defects (*e.g.*, flaws of irregular shape tend to induce cracks with subsequent failure of the casting). An extensive knowledge of foundry technique is desirable, especially where radiography is used to improve casting routines. The following types of defect are those most often encountered.

(1) **Sand Inclusion.**—Sand trapped in the casting gives an angular image on the radiograph. It is not superfluous to remark that care should be taken to make sure that it is a sand casting under examination! Sand inclusions can often be seen on the surface of castings. As shown in Fig. 25, sand inclusions are sometimes revealed with adjacent porosity. For important castings the largest dimension of an inclusion should not exceed $t/5$, where t is the casting thickness under examination. If there are a group of small inclusions approximately $\frac{1}{4}''$ apart the group is taken as representing a single large inclusion.

(2) **Slag Inclusion** is the term given to oxide or dross trapped in the casting. The radiograph will show a dark globular image of irregular outline, often with density variations within the image. Acceptance standards for this type of flaw are similar to those for sand inclusions.

(3) (*a*) **Blowhole** (gas cavity) is caused by the evolution of gas from the metal becoming trapped as the metal cools to a solid state. The image is of rounded outline and very dark. This term is applied to gas cavities greater than $\frac{1}{16}''$ in diameter.

(*b*) **Gas Pore** is similar to a blowhole but refers to cavities less than $\frac{1}{16}''$ in diameter.

(*c*) **Porosity** is the term used for the occurrence of gas cavities in the form of a cluster and is illustrated in Fig. 25.

For good quality castings the largest dimension of any gas cavity should not exceed $t/10$. For acceptable porosity a group of gas holes should lie inside a circle of maximum diameter $= t$.

(4) **Hot Tear** (Fig. 26). This applies to a fracture which takes place immediately after the metal solidifies. This type of fracture normally occurs internally. Radiographically it appears as a broken dark line with diverging branches. Hot tears are not acceptable for higher grade castings, but may be permitted for lower grades providing the tear does not exceed $t/2$ in length.

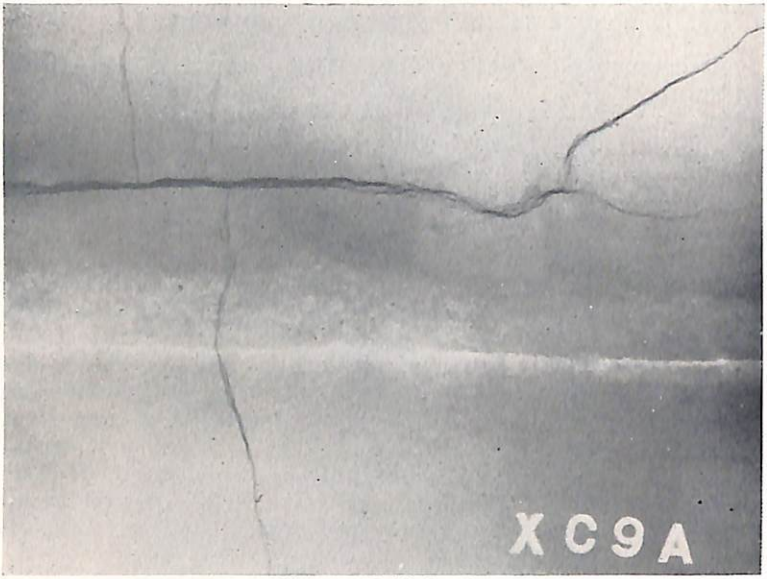


Fig. 27—Cold Crack.

Fig. 28—Shrinkage.

(5) **Cold Crack** (Fig. 27). This is a fracture occurring after the metal is cold and starts at the surface. On a radiograph it is seen as a fairly straight and sharply defined dark line. This type of defect is unacceptable for any class of casting.

(6) **Shrinkage** (Fig. 28) refers to unsound metal in that part of the casting which is the last to solidify. This defect appears on radiographs in various forms. It may occur as a pattern of long, fairly parallel voids ; sometimes scattered in clusters and often in a branch-like formation. In yet other cases it appears as a mottled effect on the radiograph. The acceptance of this defect is governed mainly by individual application. In steel castings the usual procedure is to cut out the unsound metal and repair by welding.

(7) **Micro-shrinkage** is a defect common to magnesium alloy castings. Radiographically it is seen as indistinct wavy lines or streaks following a well-defined pattern. Should this occur to any marked extent the casting will be seriously weakened and should be rejected.

Date.....	*Radiograph No*.....
Job No. :—	KV :— mA :—
Part No. :—	Cobalt/Iridium/Tantalum :— mc
Title :—	Source Size :—2 × 2 mm/4 × 4 mm/6 × 6 mm
Material :—	Film :—
Thickness :—	Screens :—
Welder :—	Source-Film Distance :—
Electrode :—	Exposure Time :—
Remarks :—	Development Time :— Temp. :—
	Developer :—
	Penetrameter :— Sensitivity % :—
	Radiographer :—
	Inspector :— Accept/Reject
	Report (see over) :—

Fig. 29—Report Card.

(8) **Sundry Defects** such as unfused chaplets and chill rods, cold shuts and core shifts, which are due often to poor foundry practice. In the case of unfused chaplets the image on the radiograph shows as a dark outline of the shape of the chaplet.

Having interpreted the radiograph the next stage is the preparation of a report. This should contain the following information :— date, job number, part number and short description of the item examined, material, thickness, radiograph number, type of film and screens used, KV and mA of X-ray set (or activity and type of radio-active isotope), S.F.D., exposure time, details of developing technique, type of penetrameter, sensitivity obtained, radiographer's name, welder's name (if applicable), concise description of defects revealed and action to be taken. A typical report card is shown in Fig. 29. It may be necessary, on occasions, to submit a sketch indicating the relation of the beam direction to the object and film, and to note any special cases such as orientation for detection of cracks. In writing reports it is essential that an attempt be made to standardise the terminology relating to defects and the extent thereof.

VIII. GAMMA-RAY SOURCES.

Radioactivity is the name given to the phenomena which accompany the spontaneous transmutation of unstable elements. In olden times it was believed impossible to break or change an atom by any means. Not only has this been accomplished, but it is known also that certain classes of atoms change their nature spontaneously (*e.g.*, the element radium changes gradually into lead). This decomposition is accompanied by the emission of rays, see Chapter II, of which the present concern is solely with gamma-rays.

Gamma-ray sources, for industrial radiography, may be classified into those which are naturally radioactive, and the artificially radioactive sources produced in the atomic pile at Harwell by the Atomic Energy Research Establishment.

Before dealing with these sources in detail it is necessary to consider certain basic concepts. The *activity*, or quantity, of a radioactive source is expressed in terms of the curie (c) or millicurie (mc). This does not apply, however, to radium where the activity is given in grammes. The curie gives the number of disintegrations occurring per second, and its size has been selected so that 1 curie is approximately equal to the activity of 1 gramme of radium.

The quantity, or dose, of the actual *gamma radiation* is expressed in terms of the roentgen (r) or milliroentgen (mr). The radiation output per disintegration by a source depends on the

nature of the gamma-ray spectrum, and varies according to the material of the source. It is, therefore, impossible in radiography to compare different sources purely by their activities. A 1 curie source of material A will emit different quantities and qualities of radiation from those emitted by a 1 curie source of material B.

Each radioactive source has its characteristic rate of decay. This is denoted by its *half-life* or, more accurately, its half-value period. That is to say the activity falls to one half of its original value after the expiration of a certain time. Consider a source of half-life = T days, the original activity of which is 2 curies. After T days have expired the activity will be 1 curie, after 2T days the activity falls to 500 millicuries; after 3T days the activity is reduced to 250 millicuries and so on. Thus the decay curve is exponential.

The naturally radioactive sources employed are radium and radon, the latter being the immediate decay product of radium.

Radium. The element radium does not of itself give out gamma-rays but only alpha particles; and the processes associated with the emission of gamma-rays from radium fall outside the scope of this work. It has a half-life of 1,590 years, and thus for practical purposes its activity may be regarded as constant. It is little used nowadays owing to the high cost and the large geometrical size of the source, the latter resulting in poor quality radiographs. When used, however, it is recommended for the inspection of steel from 2″ - 6″ thick. At a range of 1 metre the radiation is 0·83 mr per hour per mgm.

Radon. A radon source is prepared by absorbing the gas on a small charcoal granule in a glass capsule. Radon has a half-life of only 3·825 days and despite the high activities with which radon sources can be prepared the shortness of its half-life is a natural deterrent for economic use in industry. For a prolonged exposure the activity would fall considerably while the exposure was taking place. It is, therefore, difficult to establish a systematic technique for exposures with radon. On the other hand, the physical size of the source is minute and is the closest approximation attainable to the ideal point source. Quality radiographs with good definition may be produced, or short S.F.D. used to reduce exposure times. It is recommended for use on steel of 2″ thickness and upwards. At a range of 1 metre the radiation is 0·83 mr per hour per mc. Radon is a poisonous gas and the glass capsule must be handled with greatest care.

With regard to the production of artificial radioactive sources it must suffice here to give a very brief statement on radio-isotopes. Isotopes are atoms of the same element having different nuclear masses, but identical chemical properties and atomic numbers.

Isotopes of the same element each contain the same number of protons, but a different number of neutrons. The presence of an excess or deficiency of neutrons, compared with the normal value, will alter the nuclear properties of the element. There will be no effect on the chemical properties, but if the unbalance of neutrons is sufficient the nucleus will become unstable and emit radiation in returning to a stable configuration. The number after an isotope (*e.g.*, cobalt-60) denotes the atomic weight of that isotope, and this may be compared with the atomic weight of the parent element.

An important factor in the production of radioactive isotopes is the time taken to irradiate the source in the pile. The sources are supplied in standard sizes in the form of cylinders with the length equal to the diameter. The standard sizes are 2 × 2 mm, 4 × 4 mm, and 6 × 6 mm. For a given element the specific activity, in mc/gm of the substance formed, is proportional to the neutron flux of the pile and the time of irradiation. Under similar irradiation conditions the standard 2 mm, 4 mm and 6 mm cylinders acquire activity roughly proportional to their weights, and to reach the same total activity a small source must be irradiated for a longer period than a large one. While the source is being activated radioactive decay will take place, and, therefore, the activity will tend to reach a maximum. When the activity of a radioactive isotope in service falls to a value which unduly prolongs exposure time it may be returned to Harwell for re-irradiation in the atomic pile.

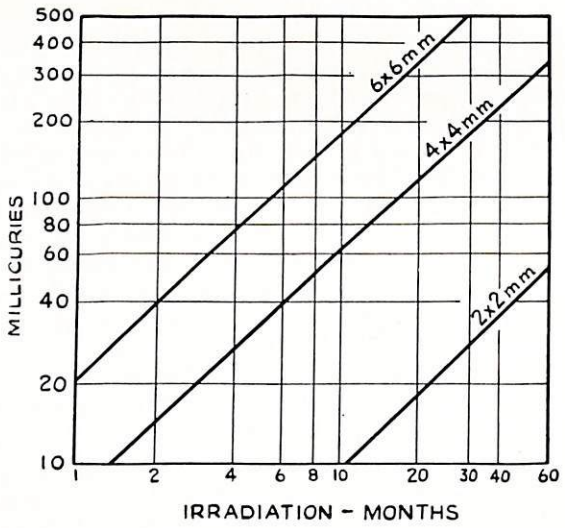


Fig. 30—Irradiation of Cobalt—60.

The radioactive isotopes now in use are as follows :—

Cobalt-60. Half-life 5·3 years. Its long half-life makes this source an attractive proposition from the economic point of view, but it takes a corresponding length of time to produce a source of high activity in the pile. The activation time graph for cobalt-60 is shown in Fig. 30. It is recommended for the examination of steel from 2″ - 6″ thickness. At a range of 1 metre the radiation from unshielded gamma-rays is 1·35 mr per hour per mc.

Iridium-192. Half-life 74·5 days. Despite its apparently short half-life this source is probably the widest used in industry. The rapid activation, see Fig. 31, and high specific activity makes possible the quick preparation of small sources. This is especially suitable for short S.F.D. work and the inspection of pipe welds. It is generally used on steel between the thicknesses of ½″ - 2″. At a range of 1 metre the radiation from unshielded gamma-rays is 0·27 mr per hour per mc.

Tantalum-182. Half-life 120 days. Similar to cobalt-60 in use in that it is mainly employed on steel between 2″ - 6″ thick. It activates more quickly than cobalt-60, as may be seen by comparing Figs. 30 and 31.

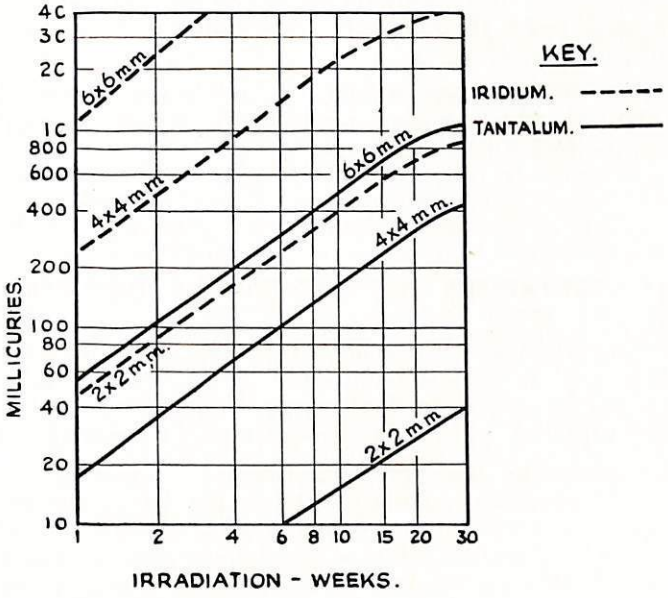


Fig. 31—Irradiation of Iridium—192 and Tantalum—182.

It is not, however, in wide use industrially. The tendency is to cover all thicknesses by holding one iridium and one cobalt source, thus rendering unnecessary the employment of tantalum. At a range of 1 metre the radiation from unshielded gamma-rays is 0·605 mr per hour per mc.

Thulium-170. Half-life 127 days. This radio-isotope is a newcomer to the range, and is the first to be suitable for the inspection of light alloys and plastics. Little work has yet been attempted with this source, but with the maximum activity at present available an exposure time of many hours duration is required to examine even the thinner aluminium sections. Extensive use of thulium-170 for industrial radiography appears to be unlikely. It is probable that it will find its greatest industrial application in the technique of measurement and control of material thicknesses.

Caesium-137. Half-life 33 years. This source is another recent product with physical properties similar to those of iridium-192. It is recommended for inspecting steel of $\frac{3}{8}$″ - 3″ thickness, and produces its best results over the range 1″ - 2″. The long half-life means that it takes a very long time to irradiate to a reasonable activity figure, and it is rather expensive. In the future, when sources of higher activities are available, it is reasonable to assume that it may supersede the employment of iridium. At a range of 1 metre the radiation from unshielded gamma-rays is 0·32 mr per hour per mc.

In the following pages radium and radon will be ignored as about 95% of industrial gamma-radiography is being carried out with the use of artificial radioactive isotopes.

IX. CONTAINERS FOR RADIOACTIVE ISOTOPES.

By comparison with the complexity of an X-ray machine the apparatus used in gamma radiography is relatively simple. In addition to the source itself, the main equipment consists of a screening container and remote control tools for manipulation.

The radioisotope is supplied by Harwell enclosed in a small Birmabright aluminium alloy capsule (see Fig. 32). The capsule shields the beta radiation, but does not affect the emission of the gamma-rays. The tag is identical for all source sizes, thus allowing for standardisation of the design of the holder inside the container. It is absolutely essential, from the safety angle, that this capsule should never be touched by hand.

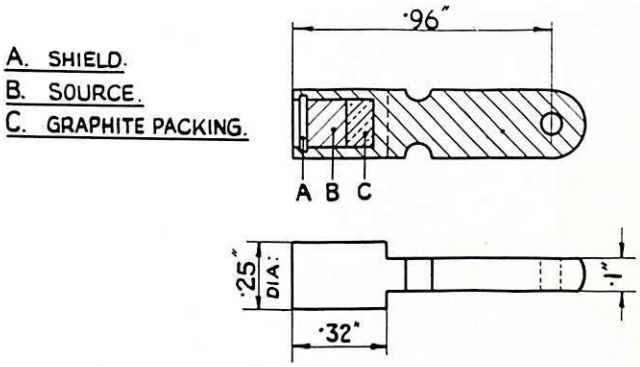


Fig. 32—Isotope Capsule.

The aluminium capsule is handled by tongs and clipped into a holder, which is then inserted into a container such as that devised by Solus-Schall, Ltd., and illustrated in Figs. 33 and 34. The holder, on the end of a long rod, is screwed into a turntable inside the container and when fully home the rod is disengaged. The capsule is then pointing inwards and only a small amount of radiation filters through the protective casing. The amount of radiation penetrating the casing will depend on the activity of the source being housed, and on the thickness and material of the casing. Lead is the material most commonly used in the manufacture of gamma-ray containers, but the model illustrated is made of a tungsten alloy. This alloy provides a greater measure of protection than lead and lends itself better to machining processes. To open the container for an exposure the T-shaped handle is turned through 180°. The handle is attached to the turntable shaft, and causes the source to appear at the open hole through which it was first inserted. Gamma-rays are now emitted to atmosphere in a stream controlled by a cone machined in the turntable. In this position the handle is automatically released from the turntable shaft and, therefore, the container cannot be carried in the operating position.

For simple exposures the source may be left in the container, but in many instances it is necessary to extract it on the end of the long handling rod. In such cases there is no check on the direction of emission of the rays, and greater safety precautions must be taken. Certain types of containers embody remote control and automatic exposure timing devices. Remote controls are necessary in many cases, especially when considering cobalt-60, where extremely powerful sources of high activity are being used. Unlike X-ray machines the use of automatic timing devices for radioisotope

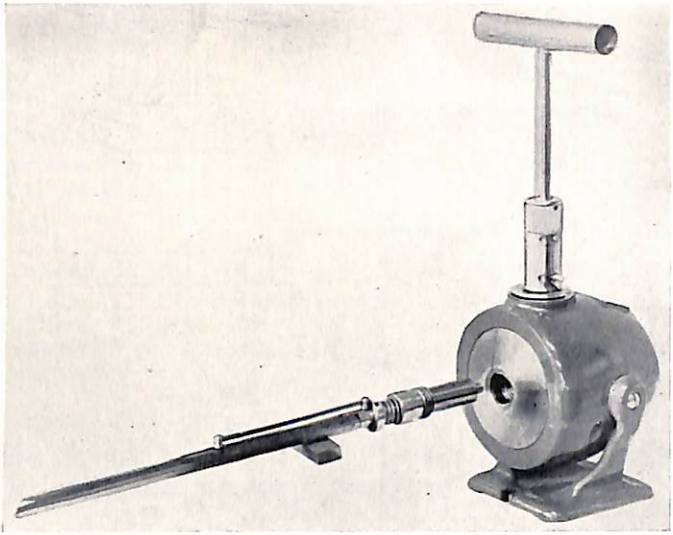


Fig. 33—Solus-Schall Container (closed) Isotope being inserted.

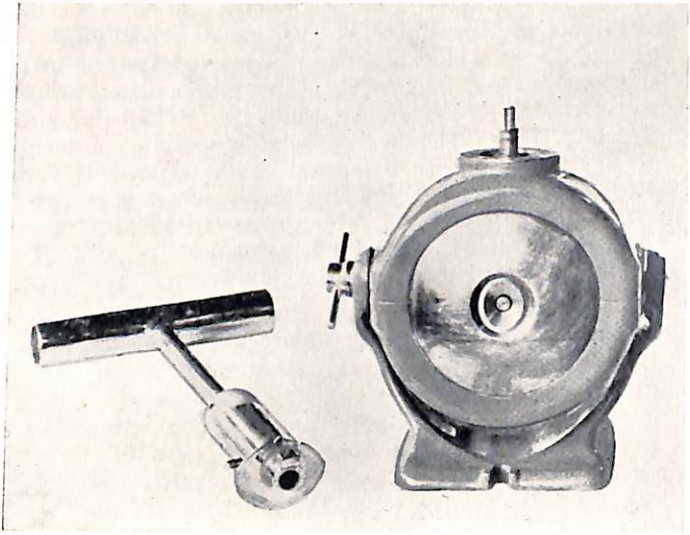


Fig. 34—Solus-Schall Container (open) Gamma-Rays being emitted.

containers is, by and large, an unnecessary refinement. It must be realised that exposures for gamma-radiography are usually very long, and consequently a slight error in timing will probably have little effect on the radiograph. Therefore, should a timing device break down a considerable loss of time and effort will result, and a false sense of security may be induced.

The spontaneous disintegration of radioactive sources cannot be accelerated or retarded. The container must, therefore, be stored in a place of safety, under lock and key, when not in use. A favourite method is to keep containers in a deep pit covered by a padlocked trapdoor. Where this is not possible a simple storage block, as designed by the authors and shown in Fig. 35, may be used. This is a concrete block which may be extended to cater for any number of containers. Each recess is lined with a cast lead cylinder of a thickness in keeping with the activity of the source stored in that recess. The recess is closed with a steel lead-lined cover, which is slotted to fit over staples cast in the concrete block and padlocked.

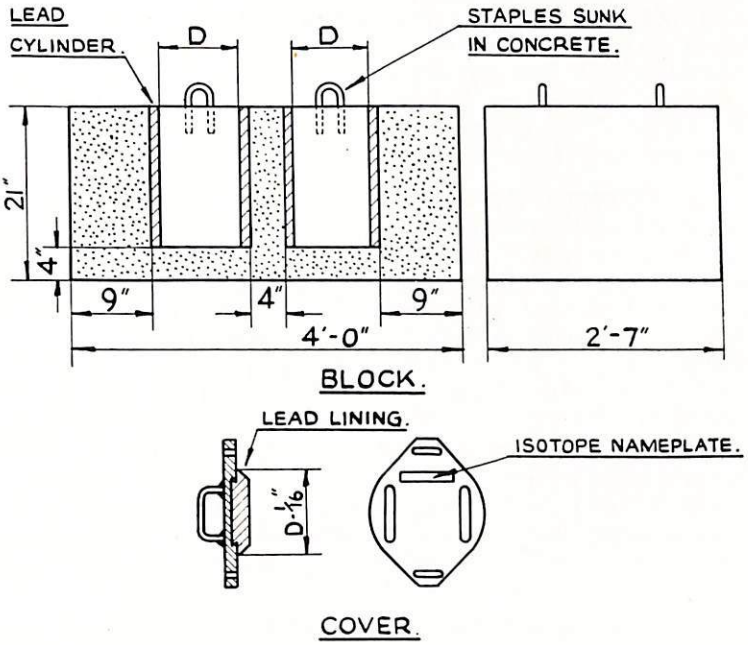


Fig. 35—Concrete Storage Block.

The subject of safety from radiation will be covered in Chapter XIII, but it should be mentioned in passing that while the ideal is to have a container giving adequate protection this is not always possible of attainment. For high powered sources a completely safe container becomes very large and heavy. Much thought is being given to this problem, and some interesting containers for use with radioisotopes of high activity are likely to be developed.

X. THEORETICAL CONSIDERATIONS (GAMMA-RAY).

At this stage it is advisable to refer to Chapter IV, and review those factors which needed consideration when using X-rays. The conditions imposed there by the KV and mA of the X-ray tube are replaced by the activity of the gamma-ray source. All the other factors discussed apply to gamma-radiography, with some slight modifications in certain cases which will be reviewed below :—

(1) **Activity of the Source.** The activity at any time will be dependent on the original activity and the half-life of the isotope concerned, and is therefore at a figure which cannot be altered when making an exposure. This is in direct contrast to X-rays where the KV and mA are variables under the control of the operator. When an isotope is supplied from Harwell it is accompanied by a decay curve, based on the half-life of the isotope, which enables the activity at any date to be determined.

(2) **Exposure Charts.** Typical exposure charts for use with cobalt-60, iridium-192 and thulium-170 are shown in Figs. 36, 37 and 38 respectively. The set conditions for these charts are stated, and any departure from these conditions will involve a change in exposure time. It will be noted that activity (mc) and exposure time are combined as a product. The procedure is to select the density required for the finished radiograph, and from the chart read off the exposure in millicurie-hours to penetrate the given specimen thickness.

As the activity of the source decays throughout its working life it will be obvious that exposure times will have to be increased. Compensation could be made for this by a reduction in S.F.D. If it is assumed, however, that an ideal S.F.D. was selected in the first instance then any future shortening would produce a radiograph of inferior definition.

(3) **The Physical Size** of the source was mentioned in Chapter VIII. Of the standard sizes the 2 × 2 mm is preferred as being the nearest to the ideal point source. Smaller sizes can be made, but they have an obvious disadvantage in that it is not possible

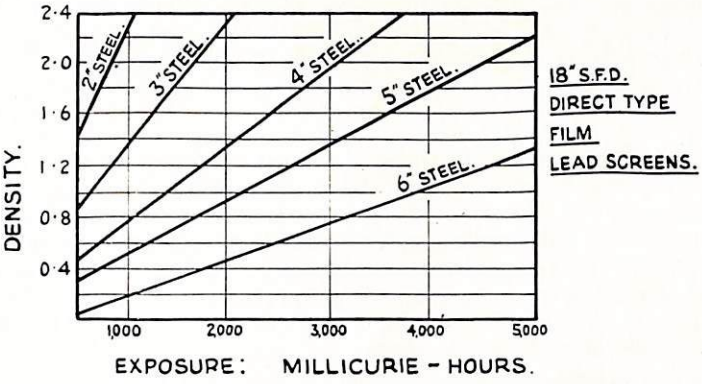


Fig. 36—Exposure Chart—Cobalt—60.

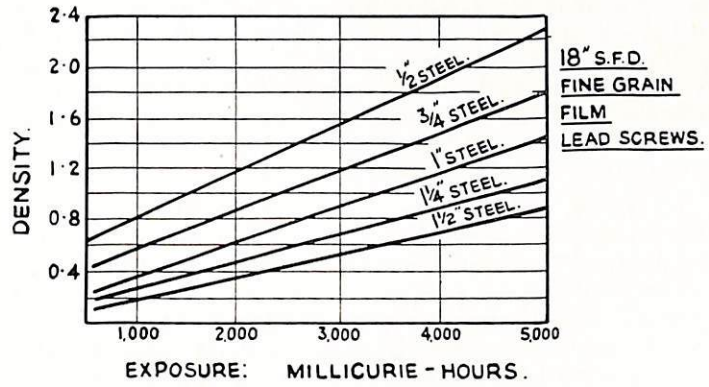


Fig. 37—Exposurt Chart—Iridium—192.

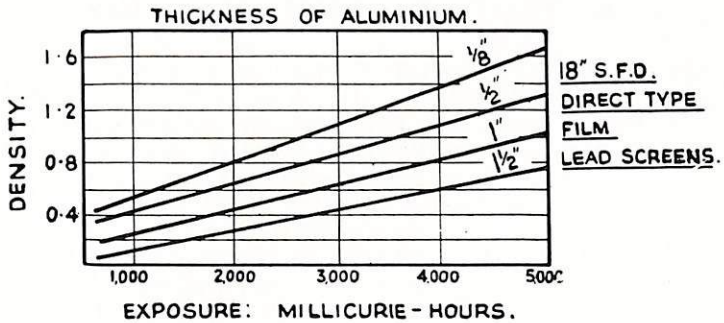


Fig. 38—Exposure Chart—Thulium—170

to irradiate them to activities of high value. It is this difficulty which causes even 6 × 6 mm sources to be used in large numbers in the engineering industry. For any given set-up, a 2 × 2 mm source can be placed nearer the film than either of the other standard sources of equal activity.

(4) **Radiographic Contrast.** It will be remembered that, for X-rays contrast decreases with increase of operating KV. As gamma-rays are comparable in wavelength to 1 - 2 million volt X-rays, they will produce radiographs of lower contrast than those given by the X-ray sets normally used in industry. Because of this lower contrast gamma radiographs are able to record wider ranges of thickness, which is of great advantage in dealing with specimens of changing sections.

(5) **Intensifying Screens.** The fluorescent type of screens are now little, if ever, used in gamma-radiography. They tend to produce radiographs of low sensitivity, and are by no means as efficient in reducing exposure times as they are with X-rays. It can be said that lead screens are always used with gamma-rays, and the most common values are ·005″ front and ·010″ back screens. An exception is made in the case of thulium-170, where screen thicknesses of ·0015″ front and ·005″ back are used in the examination of aluminium. The intensifying factor of lead screens with gamma-rays is between 2 - 4.

(6) **Films.** As fluorescent screens are not employed in gamma-radiography it is not surprising to find that the screen type film, see Chapter IV, is not greatly used. Both the direct and fine grain types of film are used, but in view of the long exposures often required with radioisotopes a further kind of film has been developed. This is a *fast, coarse grain* film which is about twice as fast as the direct type and from 8 - 10 times faster than the fine-grain.

XI. PRACTICAL ASPECTS (GAMMA-RAY).

In general the points dealt with in Chapter V apply with equal force to gamma radiography. It will be realised from a study of the exposure charts in Figs. 36-38, that exposures with gamma-rays often take hours and sometimes days when dealing with very thick sections. This, however, has an advantage in that, after setting-up, the operator is released for other duties, returning after the required lapse of time to stop the exposure. Broadly speaking, the setting-up time required with gamma-rays is less than with X-rays. As mentioned previously, when the source is removed from a container there is no check on the direction of emission of the gamma-rays. Use is made of this fact in panoramic exposures

as shown in Fig. 39. The source is placed inside an open ended tube, and the complete circumference is radiographed in one exposure by wrapping films round the outside. This obviates the several exposures, continual setting-up and difficulty of placing films inside the tube encountered with X-rays. By intelligent jig design it is possible to locate the source accurately in what may well appear to be an inaccessible position. Fig. 40 shows the adaptation of the Solus-Schall handling rod for the panoramic exposure of a welded closed-end vessel. As inserted through the location jig the isotope is shown in the dotted position. The isotope is then swung into the operating position by a central control in the rod and locked. This ensures that the source is in the very centre of the circle, and that the radiation received at all points on the circumference is equal. Many dissimilar objects may be radiographed simultaneously by placing the source on the ground, and adjusting the distance of each object from the source according to the thickness under examination, the objects being arranged in concentric circles around the source. In small bore tubes it is not advisable to place the source in the centre as the S.F.D. will be too short. In such cases several exposures will have to be taken to cover the circumference, the source being placed as shown in Fig. 41.

In view of the danger attached to working with radioactive sources it is advisable to use dummy containers or capsules when adjusting the setting, replacing the dummy by the active source when ready to commence the exposure.

In gamma radiography it is often the custom to expose two films simultaneously in the cassette. Where exposures are very long, of the order of 2 - 3 days, it is desirable to ensure that it will not be necessary to repeat an exposure. By using two films it is unlikely that identical fortuitous images will appear on both radiographs. It may be said with a fair degree of certainty, therefore, that any mark appearing on both radiographs is a defect in or on the specimen being examined. Should one film only be used and a doubt arise, regarding the interpretation of a mark on a radiograph as being either a defect or an artifact, it may be necessary to carry out another prolonged exposure. It is possible, also, by using two films simultaneously to make corrections for under-exposure. If the first film after standard development be found under-exposed, the second film may be corrected, to some extent, by developing for longer than the standard time.

For trial exposures, in cases where thicknesses may be uncertain or the location of suspect areas ill-defined, the fast, coarse grain type of film may be used to produce a guide radiograph in a short time. The necessary adjustments can then be made, and a finer grain film exposed knowing that the doubtful thickness will be penetrated, or the suspect area brought within the film area.

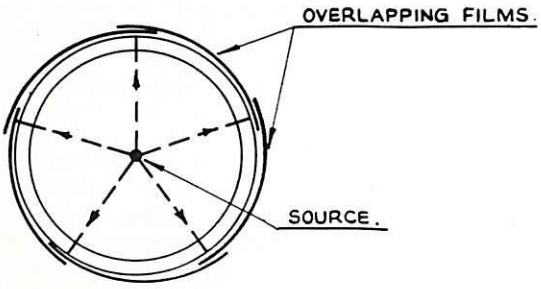


Fig. 39—Panoramic Exposure.

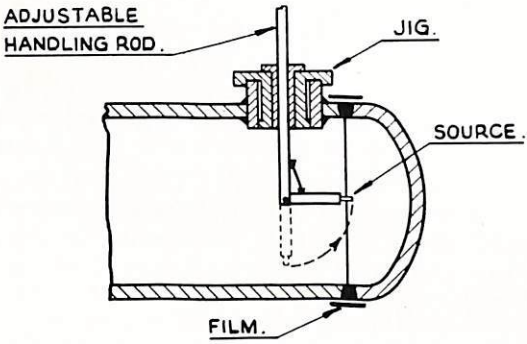


Fig. 40—Examination of Closed-end Vessel.

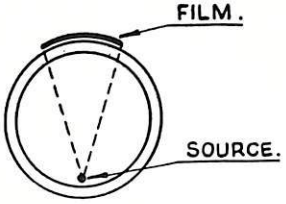


Fig. 41—Avoidance of Short S.F.D.

XII. GENERAL CONSIDERATIONS.

When specifying radiographic examination on a drawing the draughtsman should ask himself the following questions :—

(1) Why does the part require radiography? It may be to comply with the requirements of an inspecting authority or the customer; the need to investigate a critical stress point; an investigation into technique or the desire to improve the general standard of workmanship.

(2) Is the apparatus available (X- or gamma-rays) capable of doing the job? Charts for radioactive isotopes have been given, and Fig. 42 gives an idea of what may be achieved with X-ray sets.

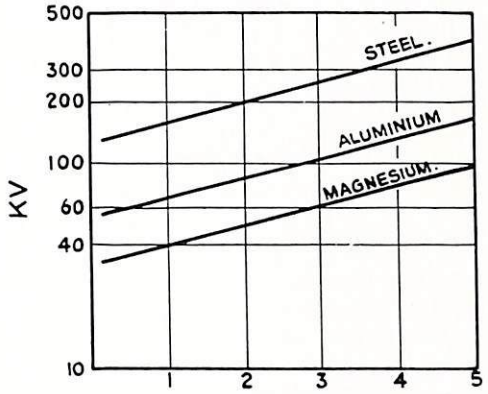


Fig. 42—Penetration Chart (X-Rays).

(3) Is radiography a practical proposition? The simple test is
  (*a*) when the source is placed outside the specimen, is it possible to place the film on the inside?
  (*b*) if the film is on the outside, can the source be inserted in the specimen?
  (*c*) will the film be near enough to the required section to give a reasonable radiograph?

(4) Would examination by some other method be more suitable? For example, magnetic or ultra-sonic methods may yield the desired results.

(5) Will the cost of radiography be justified? It is difficult to be precise as circumstances vary widely, but the cost

per exposure, including overheads, may be between 5/- and £3 10/-.

It is futile to argue that gamma-rays produce better or worse results than X-rays, or that radiography is a superior or inferior tool to, say, the ultra-sonic method. It must be realised that all methods of non-destructive testing are complementary to each other and, properly applied, all have particular fields in which they shine. Radioactive isotopes, when compared with X-ray sets, may be said to have the following advantages :—low initial cost of equipment, greater mobility and ease of handling, no maintenance costs, independence of power supply, may be used in cases which would be impossible with an X-ray set.

Generally speaking, the contrast of a gamma-radiograph is lower than a corresponding radiograph produced by X-rays and, therefore, interpretation is usually more difficult. Gamma-radiographs of steel less than $\frac{3}{4}$" thick are usually only accepted by inspecting authorities when the examination cannot be carried out by X-rays. Other things being equal, X-rays gain by the use of much shorter exposure times. The continuous emission of gamma-rays means that radioisotopes are wasting energy while not in use, a fact that is not popular with cost accountants ! It must be remembered also that radioisotopes, except in the case of thulium-170, are not suitable for the examination of aluminium and its alloys, and plastics.

Compared with the ultra-sonic method, which is rapidly making headway, radiography has the advantage of providing a permanent record of the examination and is more susceptible of correct interpretation.

These remarks would be incomplete without stressing the remarkable psychological results obtained by the use of radiography. Time and time again the introduction of this inspection technique has caused a profound improvement in the standard of work produced. This is especially true of welding where it was formerly the practice to judge quality by the external appearance of the weld. By and large it may be said that a poor looking weld will contain internal defects ; on the other hand, a weld of good outer appearance does not guarantee a sound interior. A Dutch expert (Schuil) has quoted a figure of 80% poor quality welding being reduced to 20% by systematic examination with radioactive isotopes. The authors are aware of a case of 83% rejects being cut down to 12% when the welders realised that extensive inspection was being undertaken with X-rays. Nevertheless it is encouraging to find, when much has been said of the decline of craftsmanship, that large numbers of men are keen to have their work examined by radiography. It is interesting to note that they take great pride in being able to say that their work has been proved to be perfect.

XIII. SAFETY PRECAUTIONS.

Personnel engaged on or working near to radiography must be protected against the harmful effects of X- and gamma-rays. There is no doubt, however, that the greatest danger results from familiarity breeding contempt. Provided simple precautions are taken no radiographer should suffer ill-effects.

It has been laid down that the maximum permissible dose of radiation received by the human body should not exceed 500 mr per week ; this dose corresponds to 300 mr per week measured in free air. The difference in figures arises from the fact that on exposure to an incident dose of 300 mr measured in free air the body surface actually receives 500 mr. The additional 200 mr arises from radiation scattered back by the body. The weekly permissible dose is the total radiation that may be received continuously without damage to the blood or reproductive organs. By limiting the radiation rate to 12·5 mr per hour at the working distance from the source, it will be possible to operate under these conditions for the average working week of 40 hours. It must be borne in mind, however, that it is rare for an operator to be exposed to radiation for a total of 40 hours in a week. The permitted rate of 12·5 mr per hour does, therefore, provide an additional margin of safety. It is important to note, however, that data for the usual radioactive isotopes are given for free air conditions and the figure of 12·5 mr per hour should be replaced by one of 7·5 mr per hour based on a total of 300 mr in a 40 hour week. As a full knowledge of the biological effects of radiation absorption has yet to be obtained, it is obvious that care should be taken to keep the actual dosage rate as low as possible and preferably below the present established figure.

Distance from the X-ray tube or the isotope is the simplest of safety devices, as it has been seen that the intensity of radiation falls off according to the inverse square law. Under general working conditions it is usually possible to keep well away from the source of the rays. The data given in Chapter VIII enables the radiation at any distance from an unscreened radioactive isotope to be determined. For example the recommended dosage rate is obtained at 33 feet from an unscreened cobalt-60 source of 1 curie activity. As far as possible the sources of radiation used should be the weakest necessary to accomplish the inspection required, and consideration should be given to the employment of remote controls.

It is customary for a radiographer to wear a small dosemeter or a film badge during working hours. The dosemeter may be attached to the wrist or carried in a pocket ; in the case of film

badges these are submitted to the National Physical Laboratory at regular intervals for measurement of the dose received. In addition all personnel engaged on radiography should undergo a total and differential blood count before commencing this type of work, and thereafter at regular intervals not exceeding six months. The value of periodic blood counts lies in the fact that blood changes are usually the first warning of impending damage to one's health. For checking radiation levels to determine safe working distances a radiation monitor, such as the Ekco model shown in Fig. 43, is used. Where an exposure is being made in an open shop the danger areas should be roped off and prominent warning notices displayed.

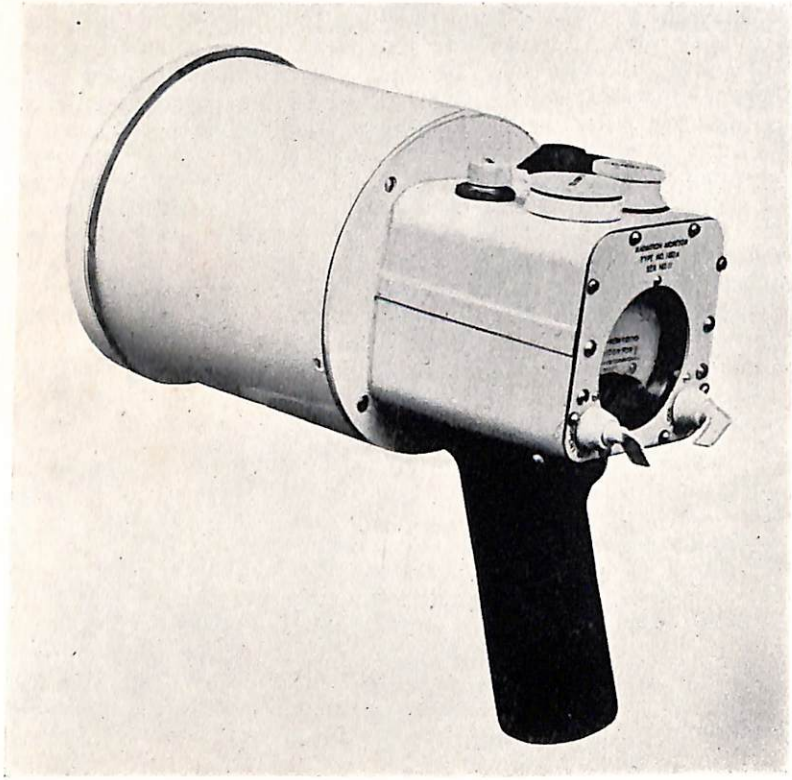


Fig. 43—Ekco Radiation Monitor.

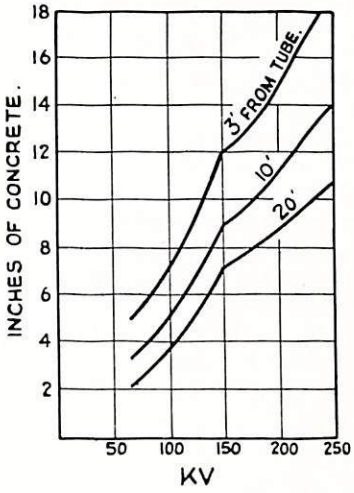


Fig. 44—Concrete Shielding. (X-Rays).

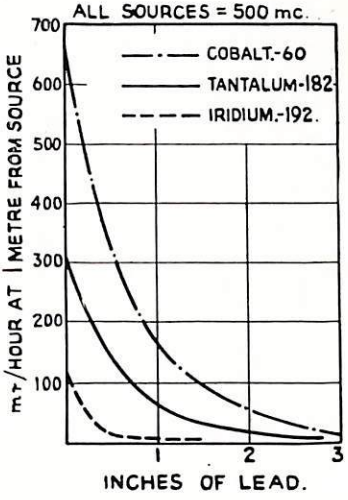


Fig. 45—Lead Shielding. (Radio-Isotopes).

Protective materials for buildings, isotope containers and storage blocks have effective screening properties in approximate proportion to their densities. Thus if red brick is taken as having an effectiveness of unity, then concrete is 1·2, barium plaster 1·8, lead 7·0 and tungsten alloy 10·5. Fig. 44 shows the thickness of concrete required to reduce the dosage rate to 12·5 mr per hour with direct radiation from an X-ray tube. Fig. 45 indicates the effect of lead shielding on the radiation of different radio-isotopes at a distance of 1 metre from the source.

Buildings must be designed so that no harmful radiation can be traced on the outside. For X-ray sets the controls should be situated in a small radiation proof cubicle with a lead-glass observation window. Electric relays must be provided on all doors to prevent entry into the building while an exposure is being made. It is advisable to consult the National Physical Laboratory for their recommendations during the early stages of designing buildings for radiography.

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26. 1″ ,, ,, ,, (30 ton yield).
27. ¾″ ,, ,, ,, (40 ton yield).
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